

Using High Resolution Geodetic Imaging Data to Develop Next-Gen PFDHA

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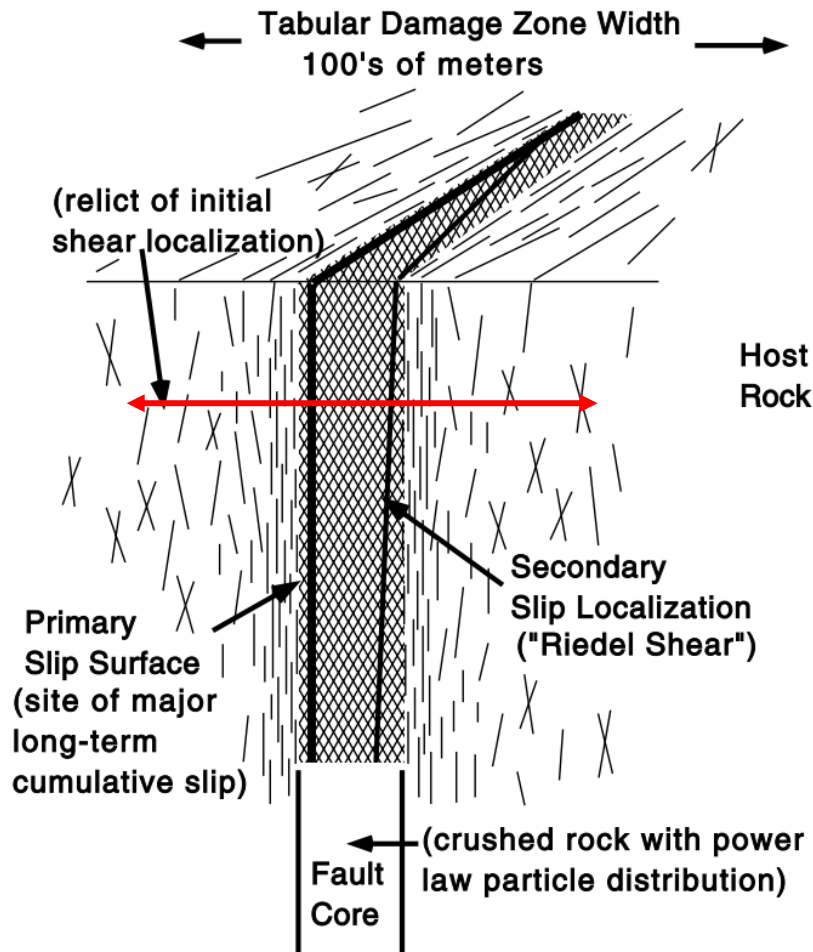
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Donnellan, Andrea Jet Propulsion Laboratory, California Institute of Technology

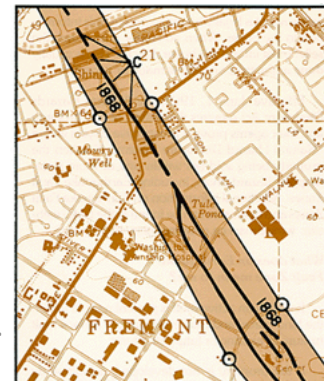
Background on PFDHA

Ben-Zion & Sammis (2003)

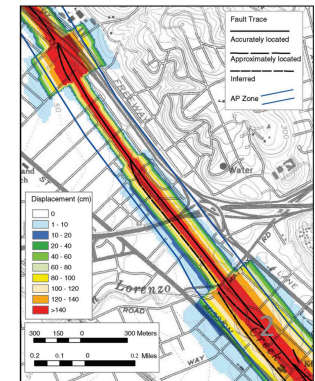


- What is PFDHA?
 - Probabilistic fault displacement hazard analysis
 - Characterize the probability of distributed faulting
- Current approach to mitigating fault ruptures → **AP zones:**
 - Limits new construction.
 - **Issue:** Do not provide guidance for mitigating structural damage to infrastructure that has to cross faults.
- **PFDHA provides:** understanding of intensity of distributed rupture across fault zone

AP zone



PFDHA

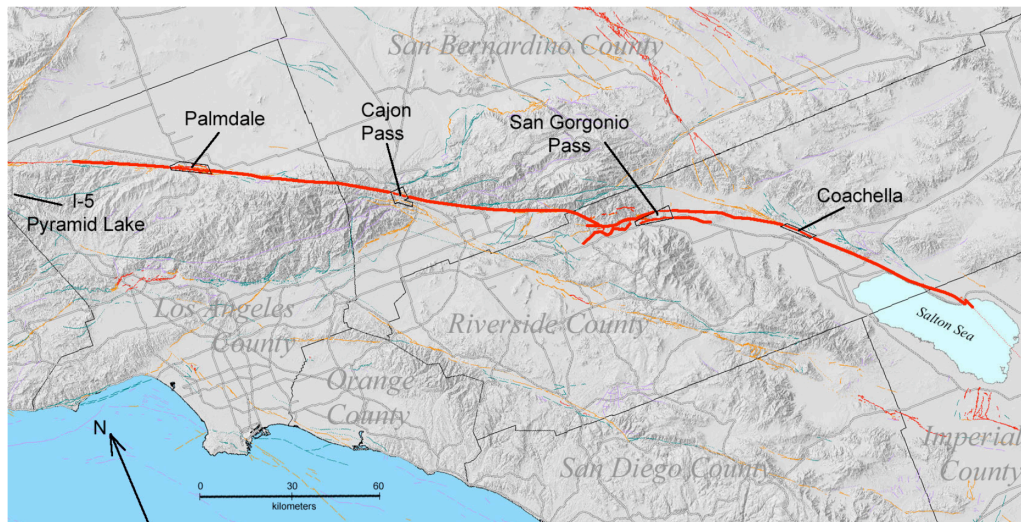
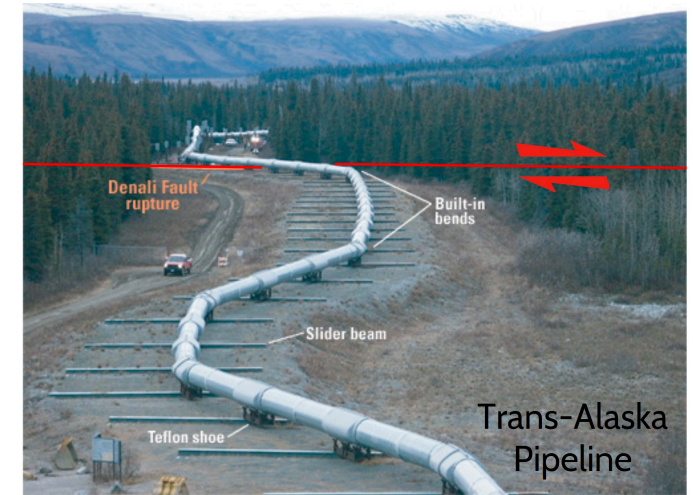


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Petersen et al. (2011)

Applications of PFDHA

- Distributive infrastructure
 - Roads
 - Pipes – oil, water, utilities
 - telecommunications
 - Buildings already situated near faults.



Holds importance.
for designing
more resilient
cities

Introduction

- **Aim:**

- Use high-res. geodetic techniques to image fault zone + distribution of faulting to get improved probabilities.

Field survey measurements



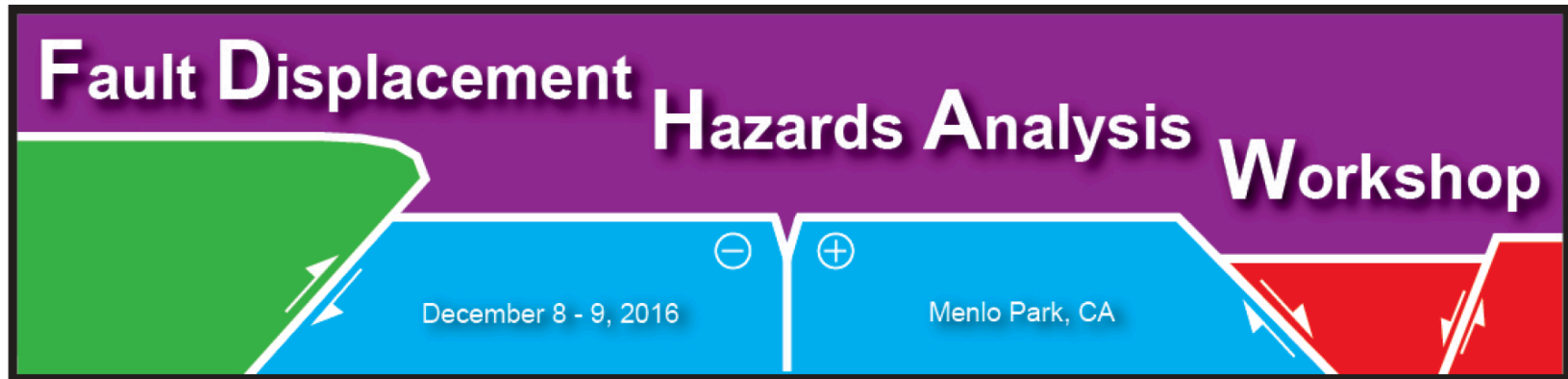
- **Motivation**

- Current PFDHA models constrained from traditional field data. Geodetic data → more data + lower uncertainty → better predictive power.

Outline

- Background: current PFDHA + data limitations
- Geodetic Imaging method
- How we measure distributed faulting
- How we constrain probabilities
- Preliminary results
- What's next...

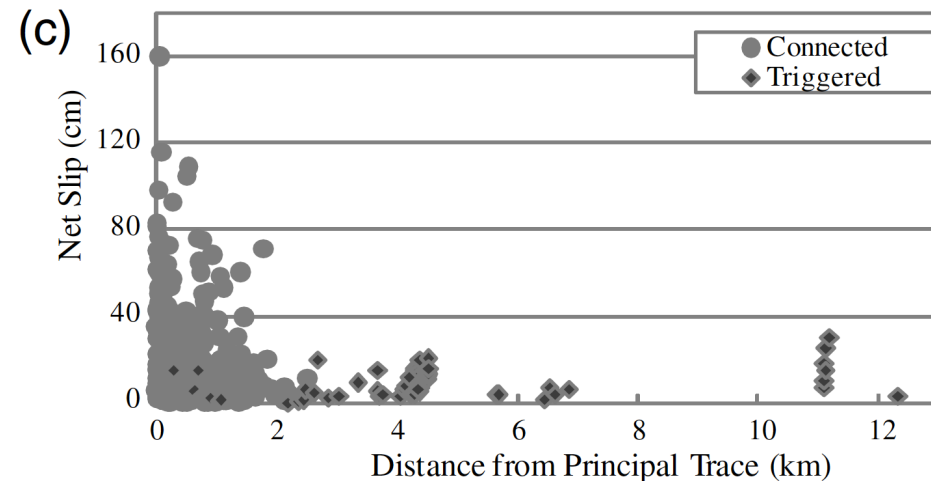
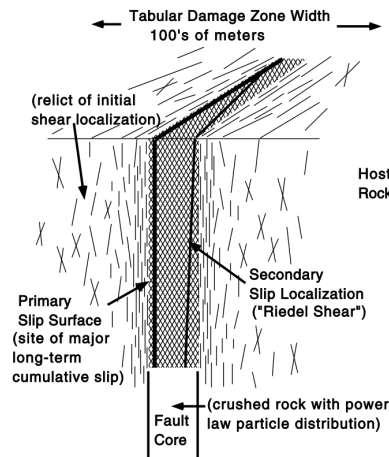
Renewed efforts in PFDHA



- **2016 USGS workshop – FDHA**
- **Faults2SHA Working Group** - Bridge gap between observationalists + modelers to improve reliability of fault hazard assessment.
- **UCLA**
- **IPGP - Paris**
- **Italy**
- **Aim:**
 - Update fault database from recent earthquakes
 - Use new data to improve PFDHA models → provide more reliable estimates of hazard to risk modelers and engineers

Current approach to PFDHA

Petersen et al. (2011)



$$\lambda(d \geq d_0)_{xyz} = \alpha P[sr \neq 0|m] \int_r P[d \neq 0|r, z] P[d \geq d_0|r, m, d \neq 0] f_R(r) dr$$

Annual return (yr⁻¹)

Probability of surface rupture (Wells & Coppersmith, 1994)

Probability faulting occurs

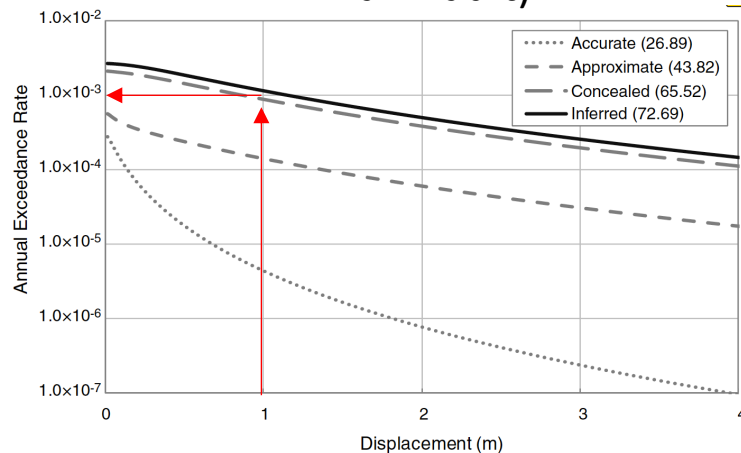
Probability displacement exceeds some amount.

Mapping uncertainty

1. Gather + compile lots of field observations of faulting
2. Look at how displacement 'attenuates' away from main primary fault
3. Use fault trace mapping to constrain probability faulting occurs

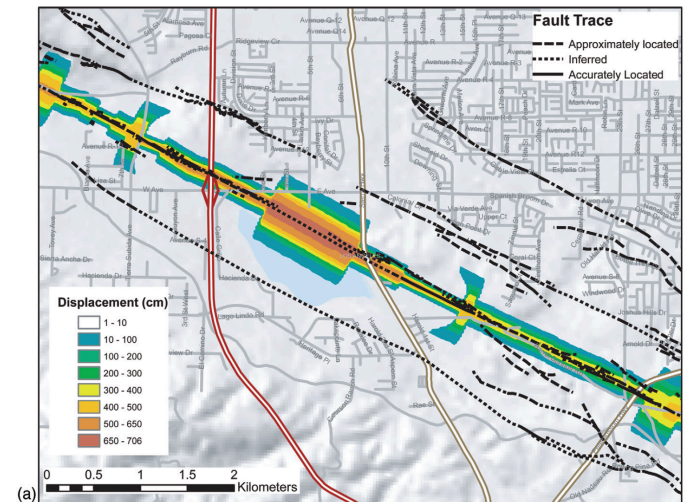
PFDHA output

Hazard curve (160 m away from main fault)



Petersen et al. (2011)

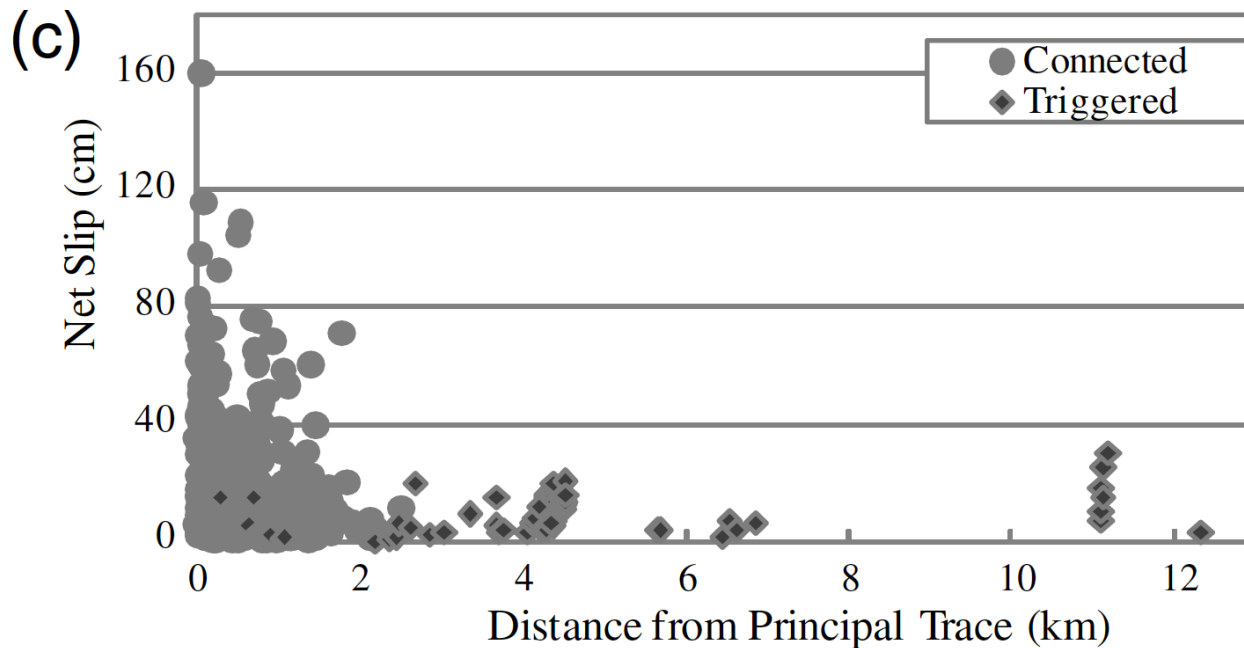
Displacement Hazard map



Petersen et al. (2011)

- Hazard curve = annual frequency of occurrence of faulting at some distance from the fault.
- Annual frequency is 0.001 (yrs), or 0.1% in 1 yr, of experiencing 1 m of displacement or more at a distance (160 m) away from primary fault.
- Displacement map: 10% probability of exceedance in 50 years.

Data limitations for PFDHA

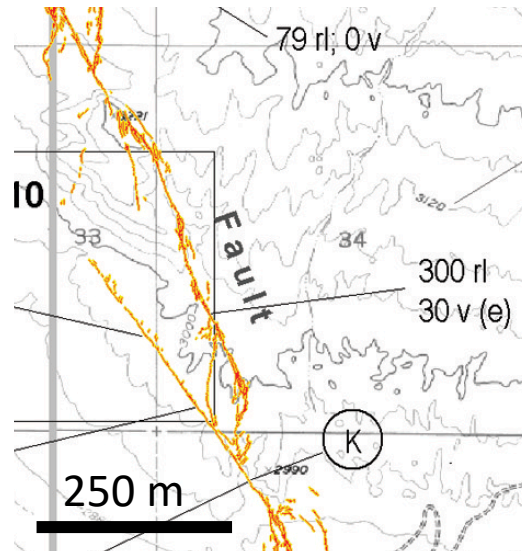


Petersen et al. (2011)

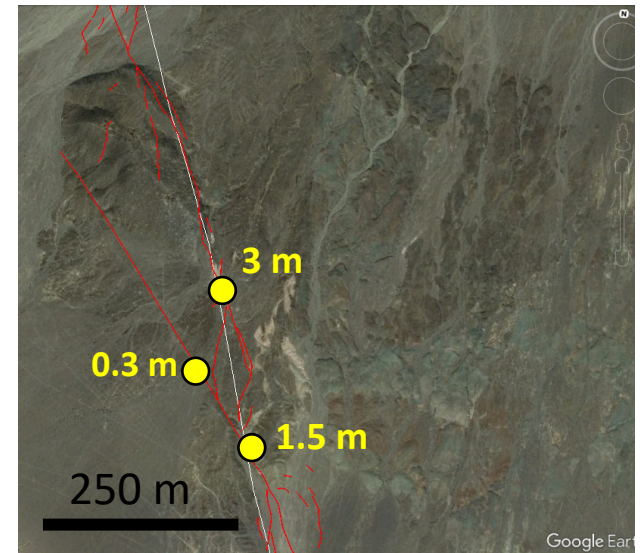
- Field data constrain: attenuation of distributed faulting with distance.

Current Data Limitations: Sparse measurement

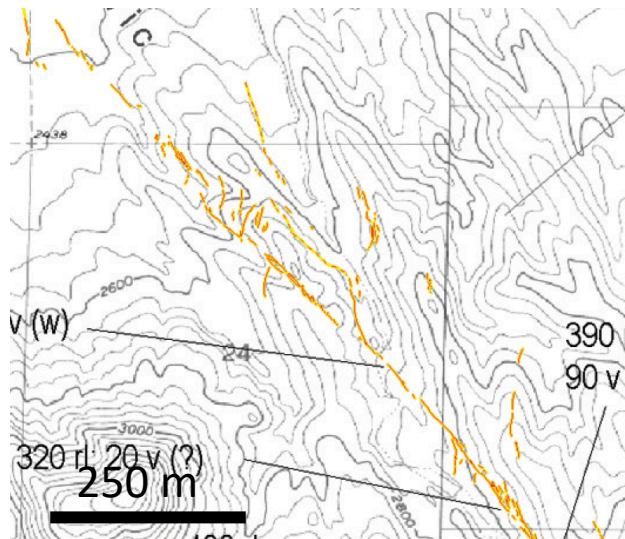
Field trace mapping



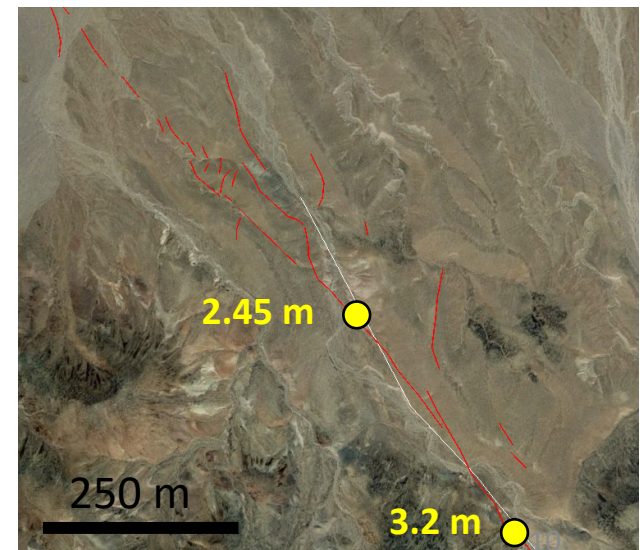
Field offsets



- Challenging to measure offsets without clear cultural or geomorphic features

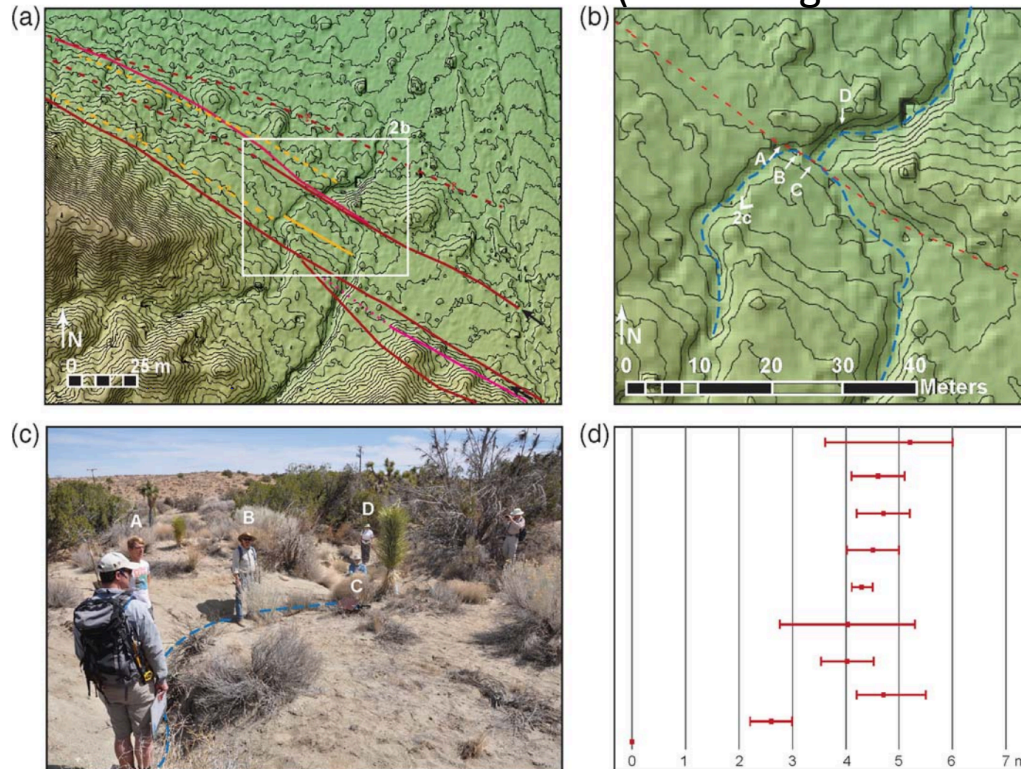


Treiman et al. (2002)



Current Data Limitations: Uncertainty & Subjectivity

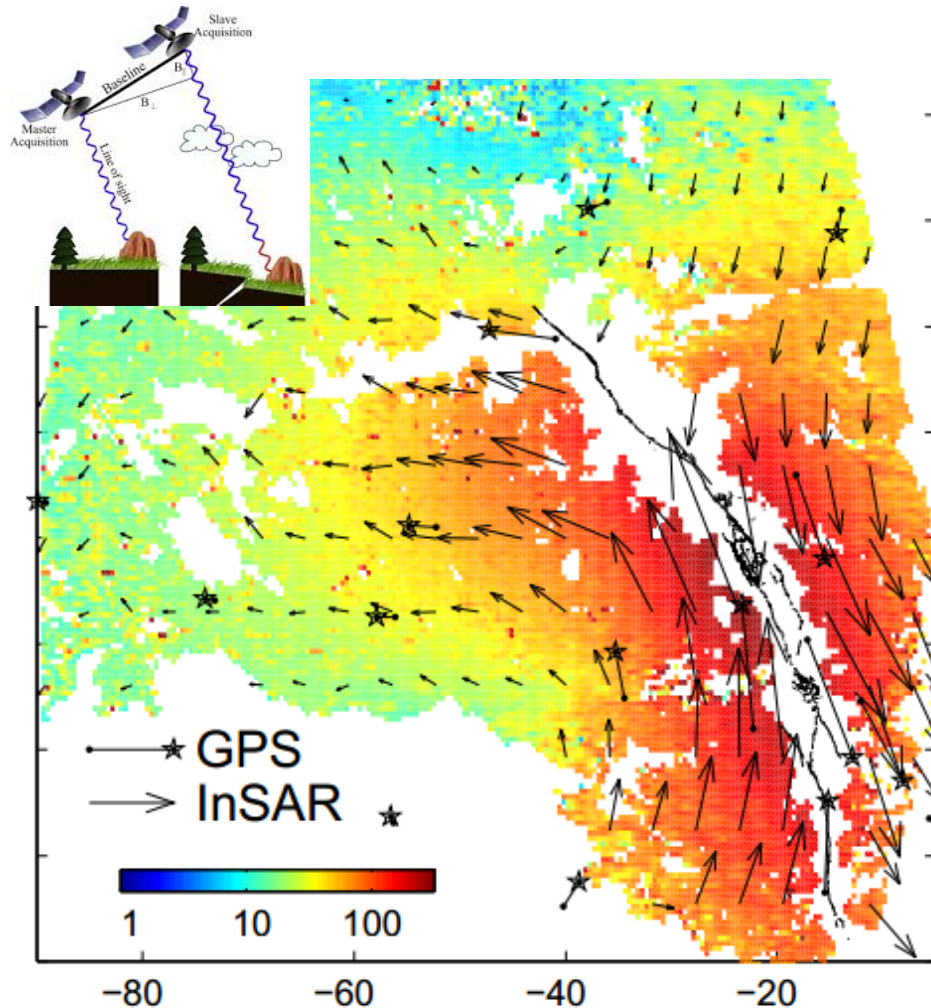
San Andreas Fault test site (NW along-strike from Pallett Creek)



Scharer et al. (2014)

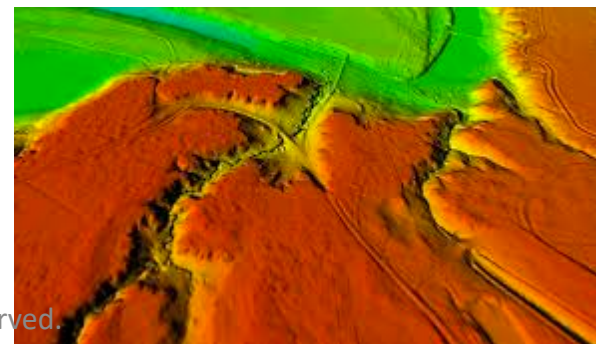
- Measuring offset geomorphic feature requires experience
- Interpretation of how to restore offset/ matching features across fault varies
- How to apply uncertainty (min/max, 2 sigma) and how much varies

New approach: Use geodetic imaging data



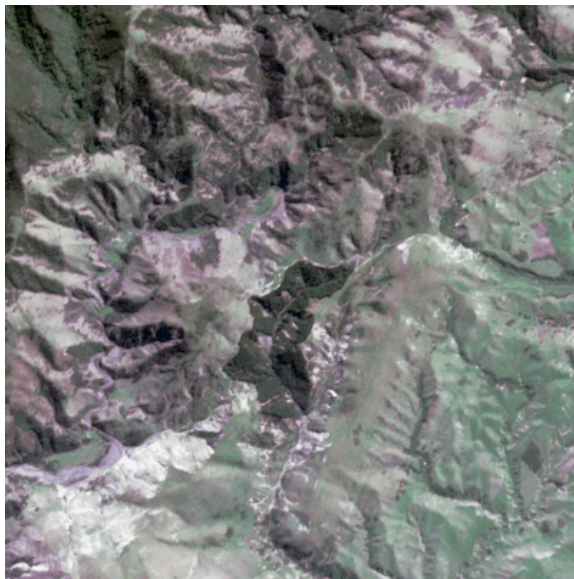
Fialko (2009)

- InSAR good at capturing far-field surface motion.
- Decorrelates in near-field → poor constraint
- Complementary methods: Image correlation + lidar differencing



Optical image correlation (COSI-Corr)

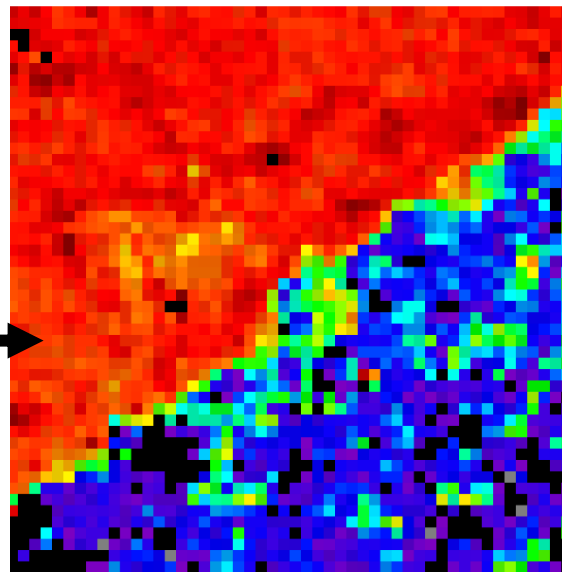
Before and After



M_w 7.8 Kaikoura, NZ

2 km

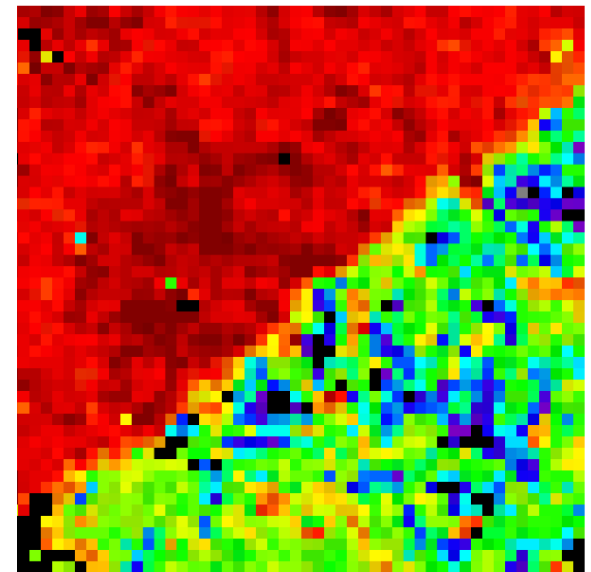
East-west



-5 m 5

Sensitive to horizontal motion

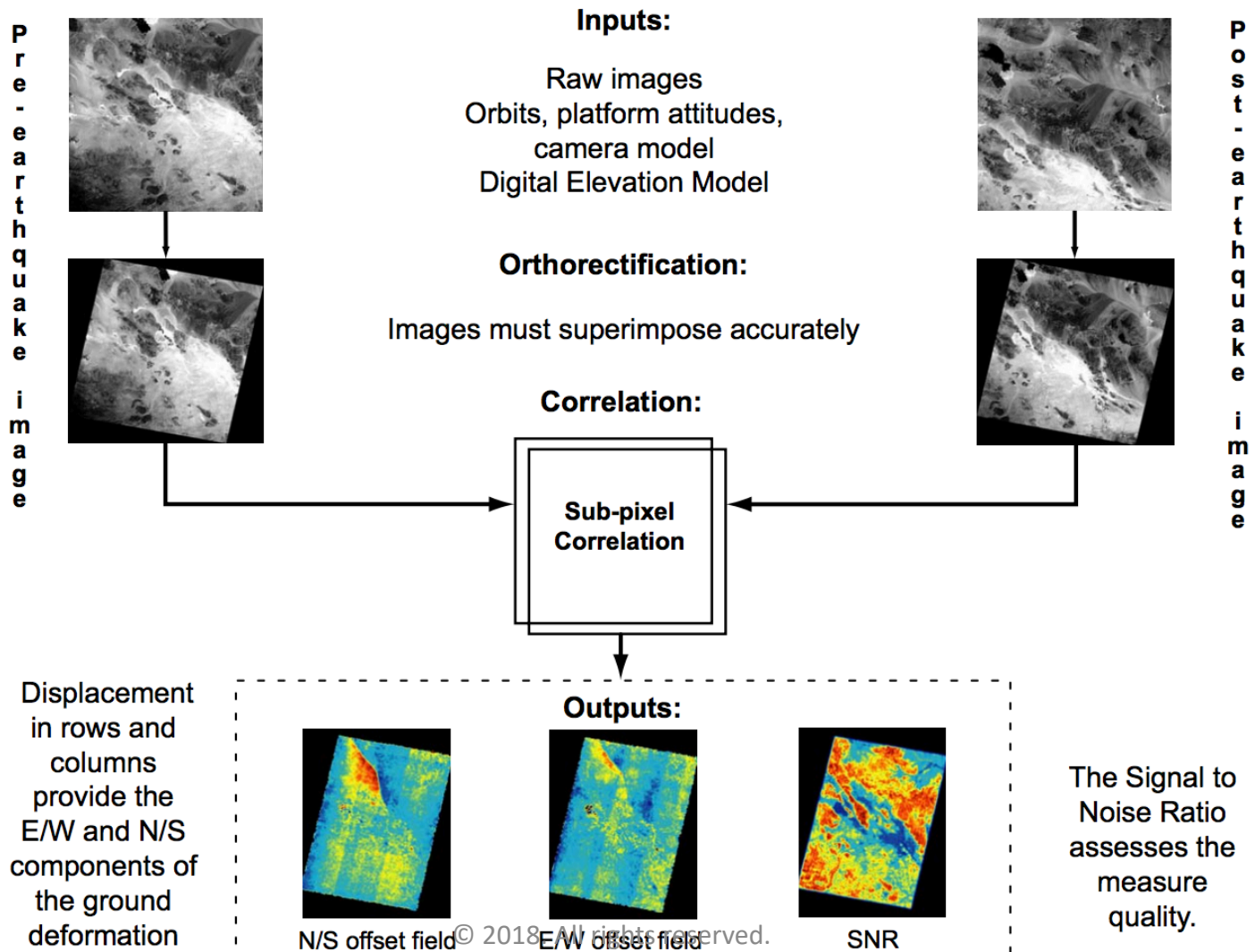
North-south



-5 m 5

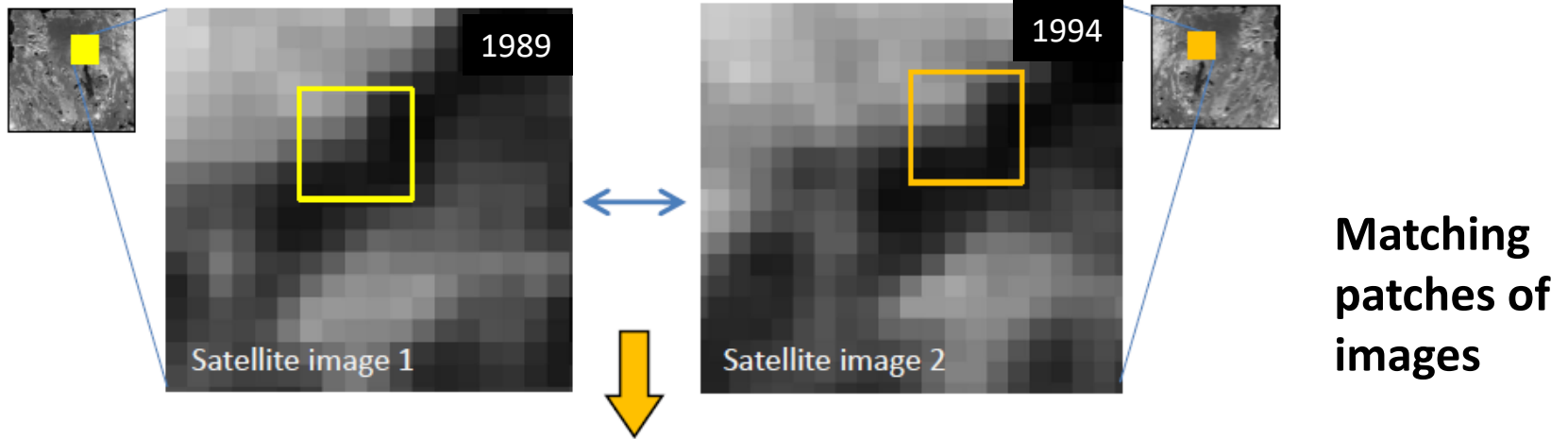
Noise = $1/10^{\text{th}}$ image resolution
e.g., Landsat = 15 m
Can resolve motion of 1.5 m

Processing overview



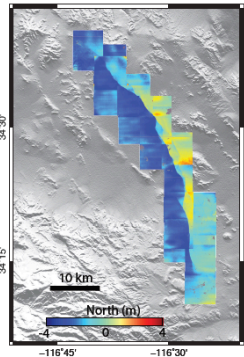
Correlation method

Image correlation:

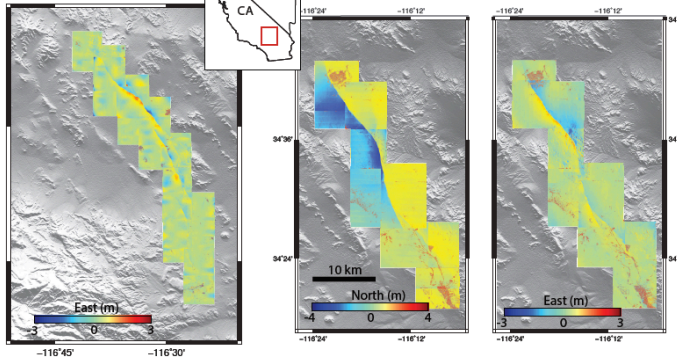


Geodetic Data for PFDHA

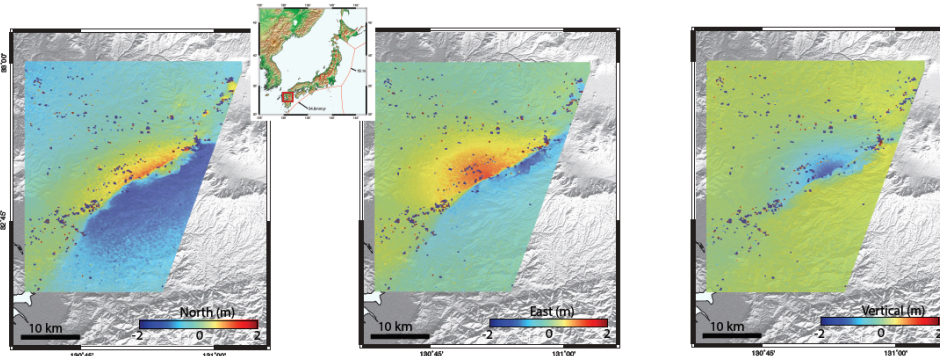
1992 Mw 7.3 Landers



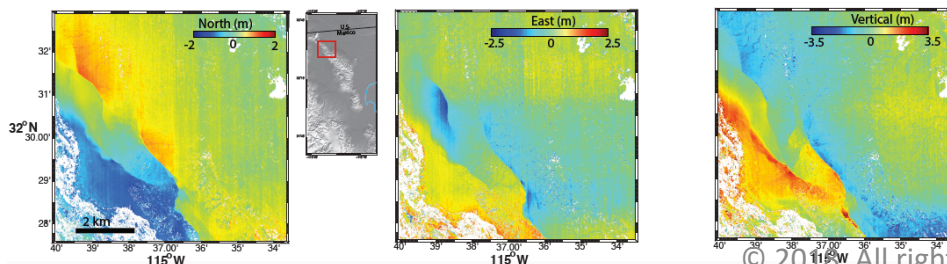
1999 Mw 7.1 Hector Mine



2016 Mw 7.1 Kumamoto

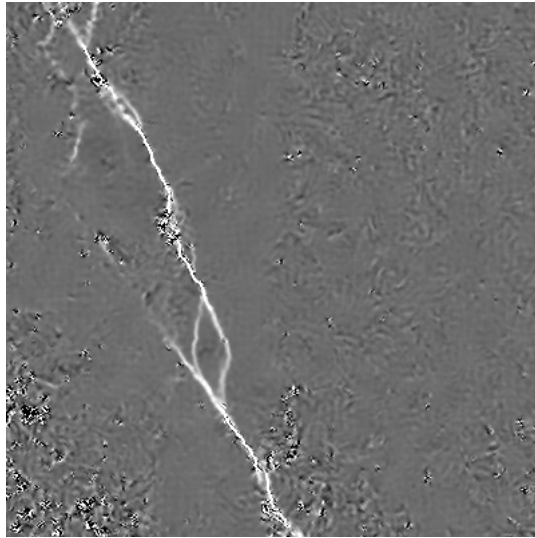


2010 Mw 7.2 El-Mayor Cucapah

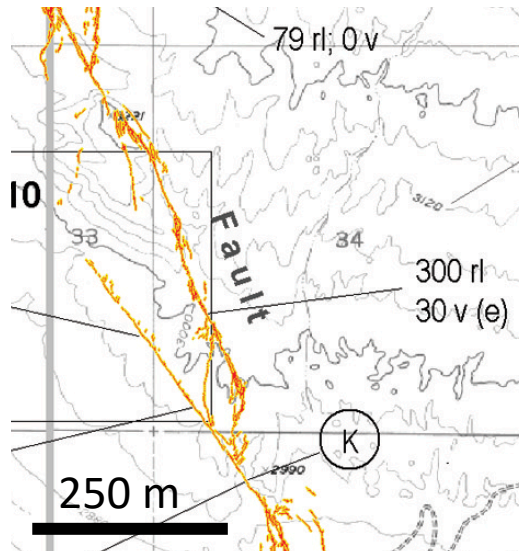


- 4 earthquakes so far
 - $n = 3,000$
- Plan to gather 10 in total of a range of M_w and tectonic settings (all strike-slip)
 - $n = 7,000-8,500$
- Data will come from a mix of:
 - sensors
 - image resolutions
 - matching techniques

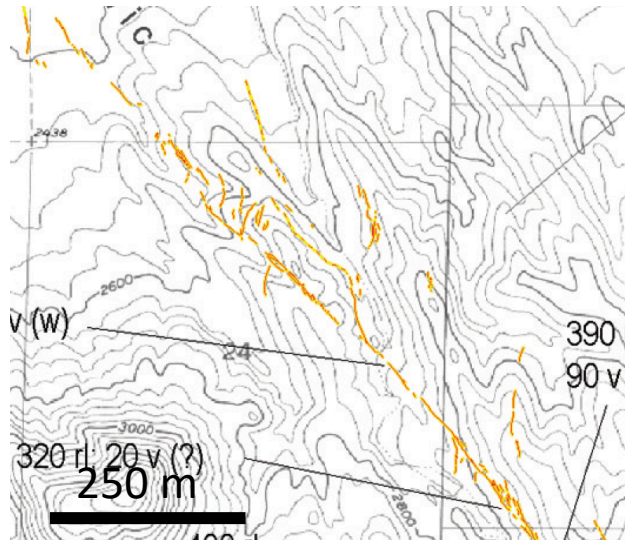
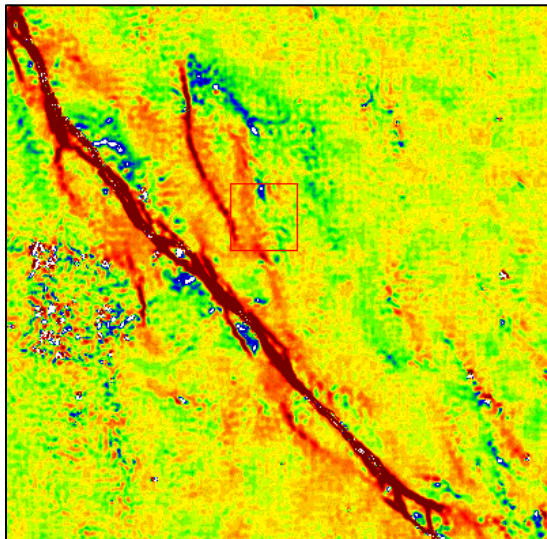
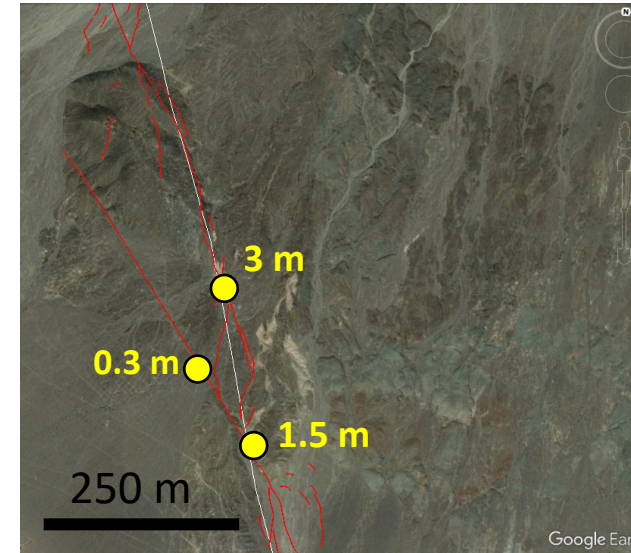
Geodetic data (strain map)



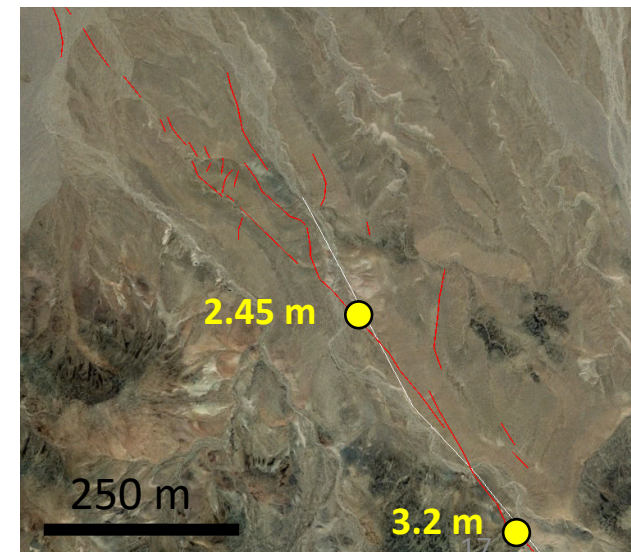
Field trace mapping



Field offsets

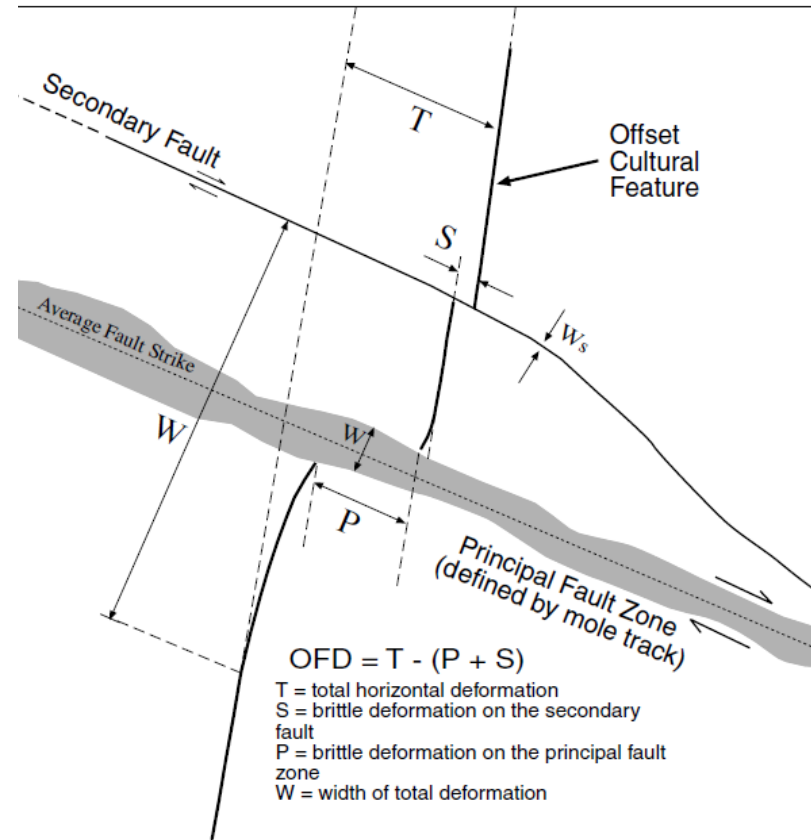
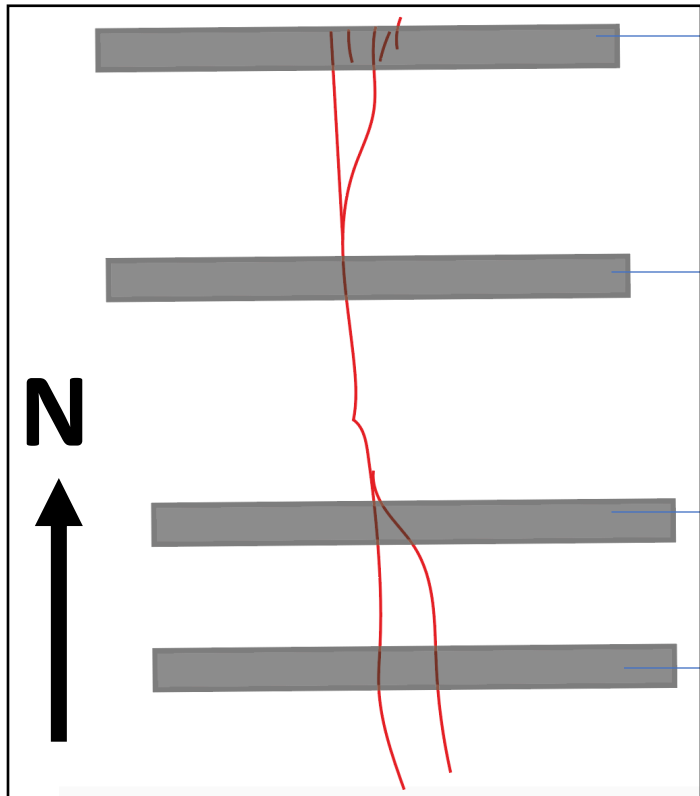


Treiman et al. (2002)



Measuring shear strain

Mapped fault traces



Rockwell et al. (2002)

Different approach for calculating hazard curve

- Geodetic approach is different but analogous to that used for field data
- **Problem:** We need to constrain two probability terms

PFDHA using field data

Mapping uncertainty

$$\lambda(d \geq d_0)_{xyz} = \alpha P[sr \neq 0 | m] \int_r P[d \neq 0 | r, z] P[d \geq d_0 | r, m, d \neq 0] f_R(r) dr$$

Petersen et al. (2011)

PFDHA using geodetic data

This study

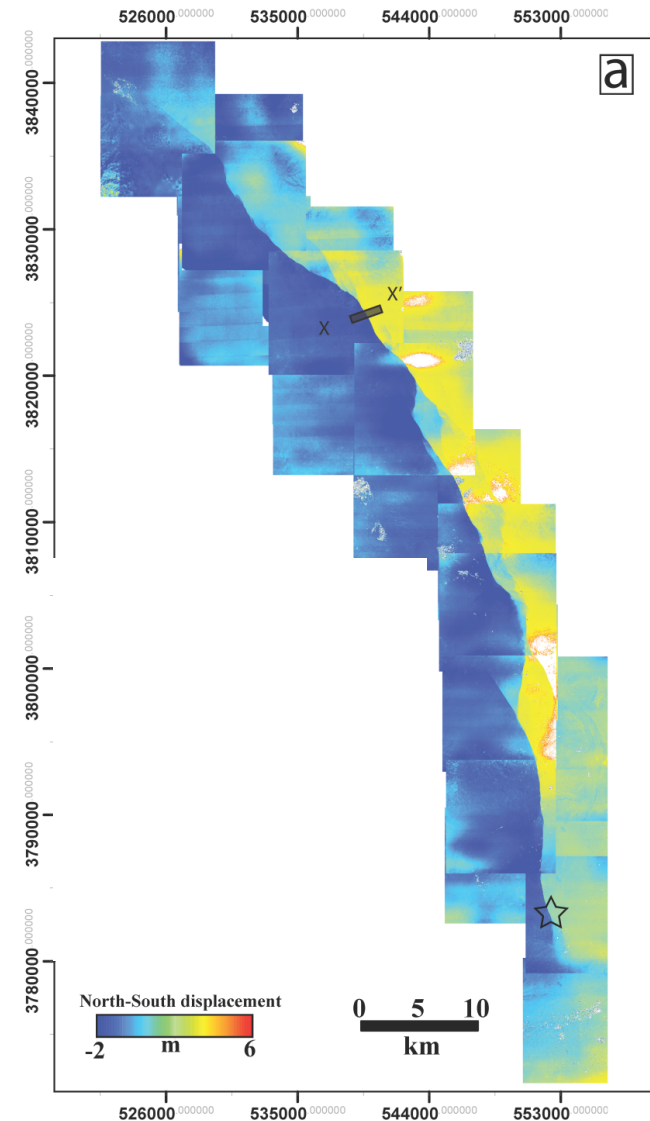
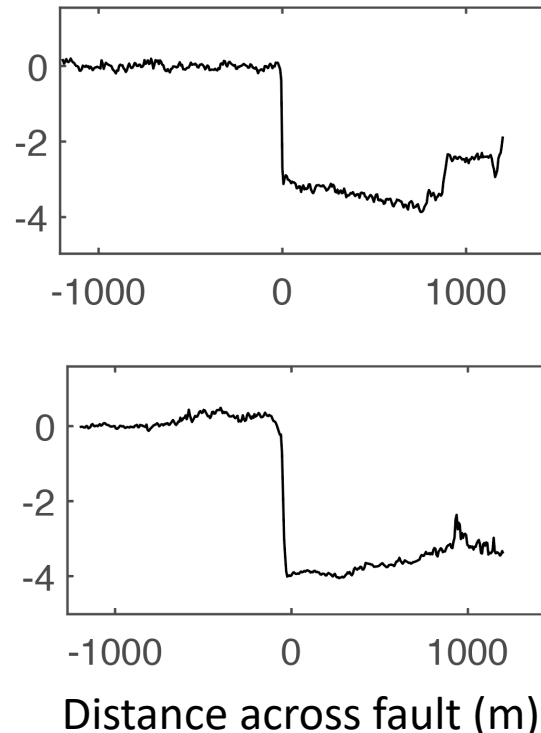
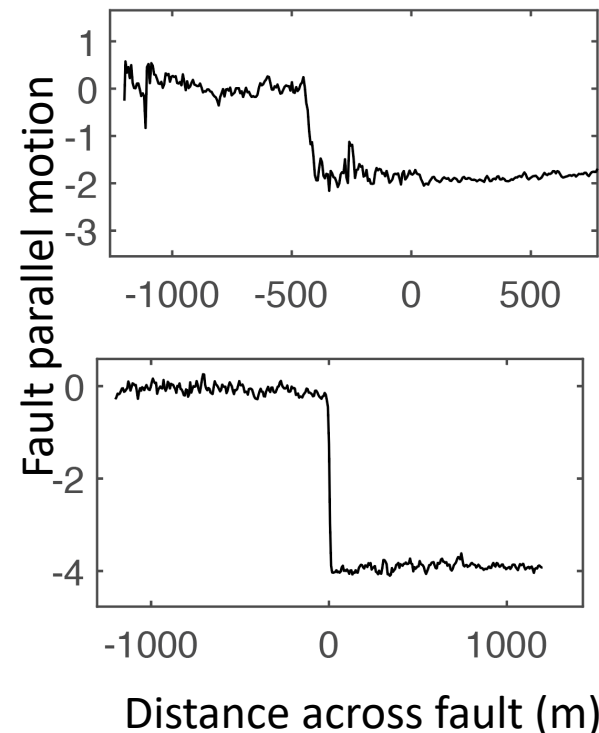
$$\lambda(\varepsilon \geq \varepsilon_o)_{xyz} = \alpha P[sr \neq 0 | m] P[\varepsilon > \varepsilon_{inelastic} | r, z] P[\varepsilon \geq \varepsilon_o | r, m, \varepsilon_{inelastic}]$$

Probability inelastic strain occurs (i.e., failure of material)

Probability strain exceeds some amount of interest

Displacement profiles

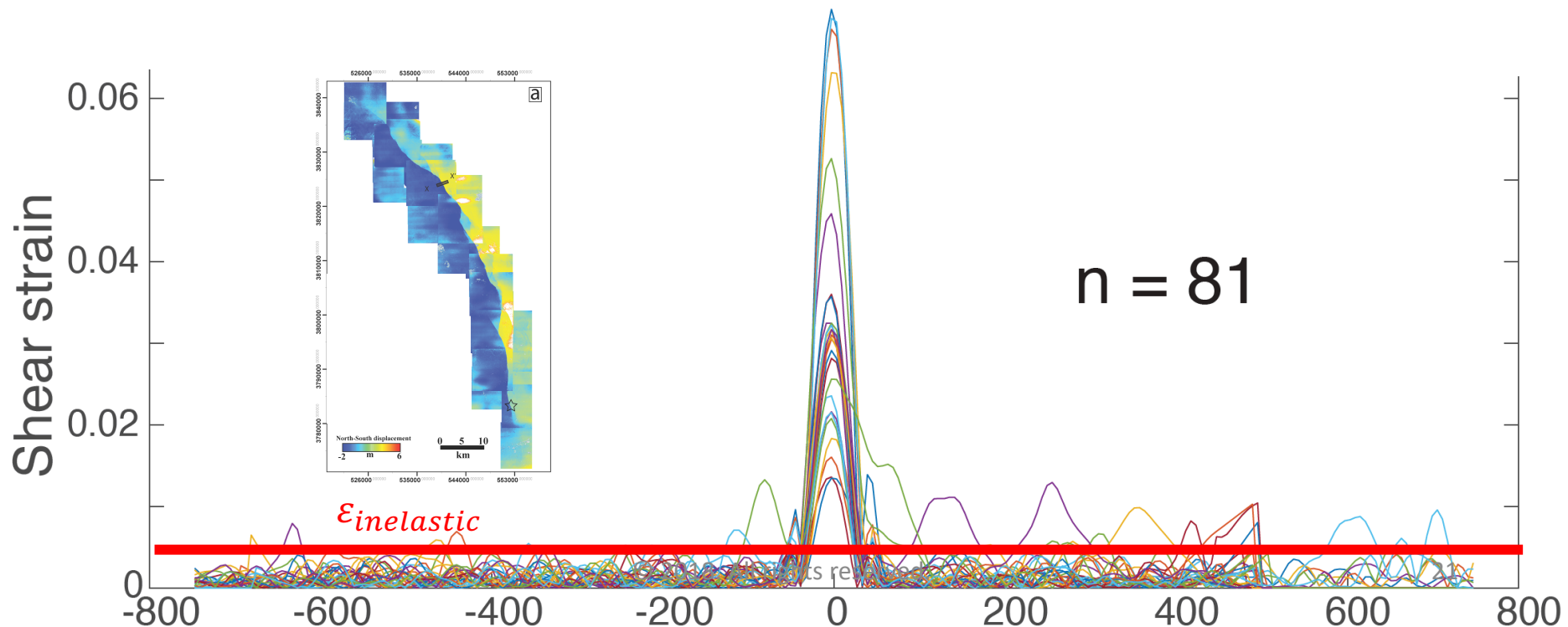
- Fault-parallel displacement profiles → strain profiles



Generating strain profiles

- Compile all strain profiles along rupture together
- We choose a value to:
 - Discern what's inelastic vs elastic
 - And what is noise vs robust

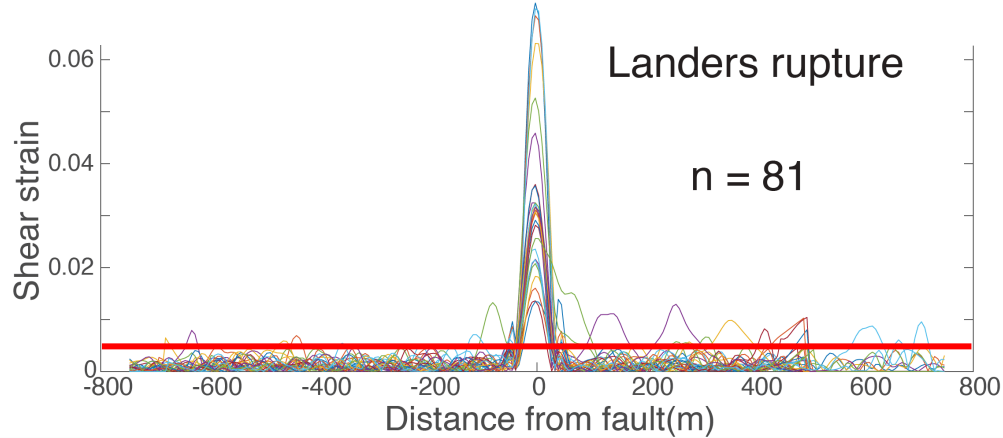
$$P[\varepsilon > \varepsilon_{inelastic} | r, z]$$



Probability strain is inelastic

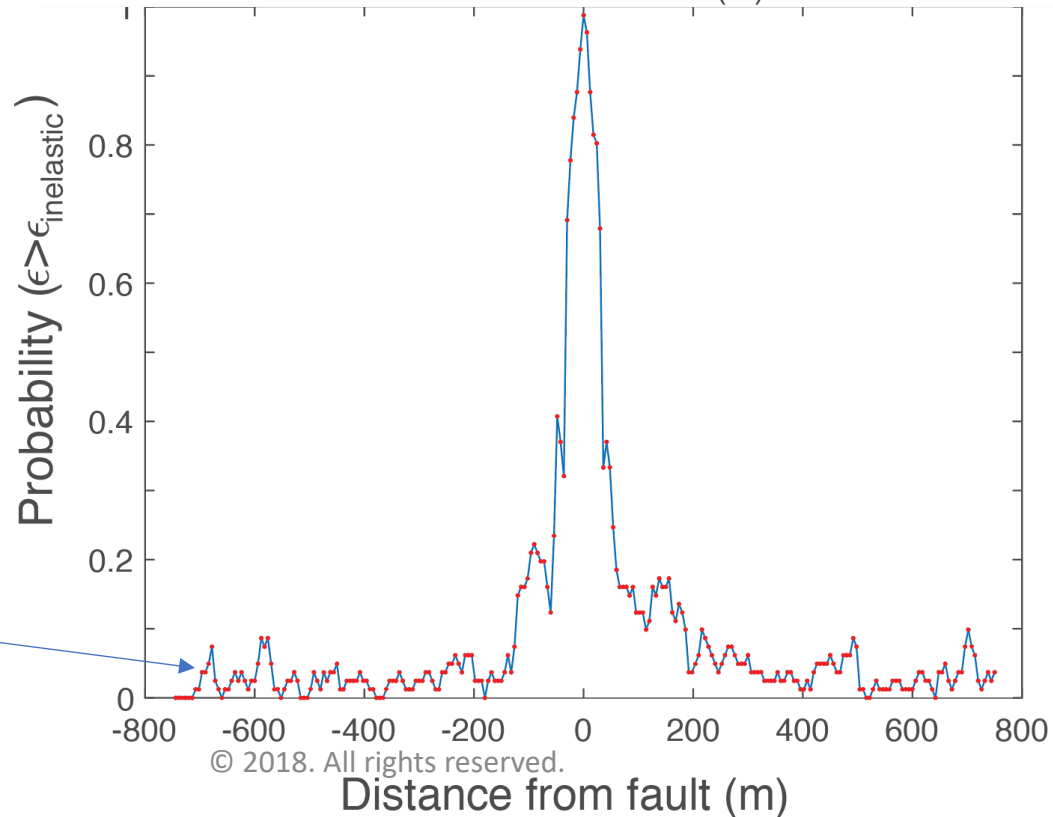
Count number of profiles that exceed a given threshold value

$$\varepsilon_{inelastic} = 0.004$$



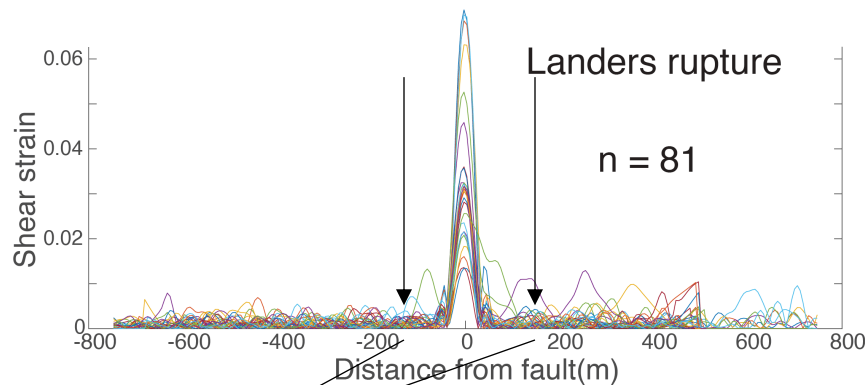
Derive empirical probability strain is inelastic:

$$P[\varepsilon > \varepsilon_{inelastic} | r, z]$$

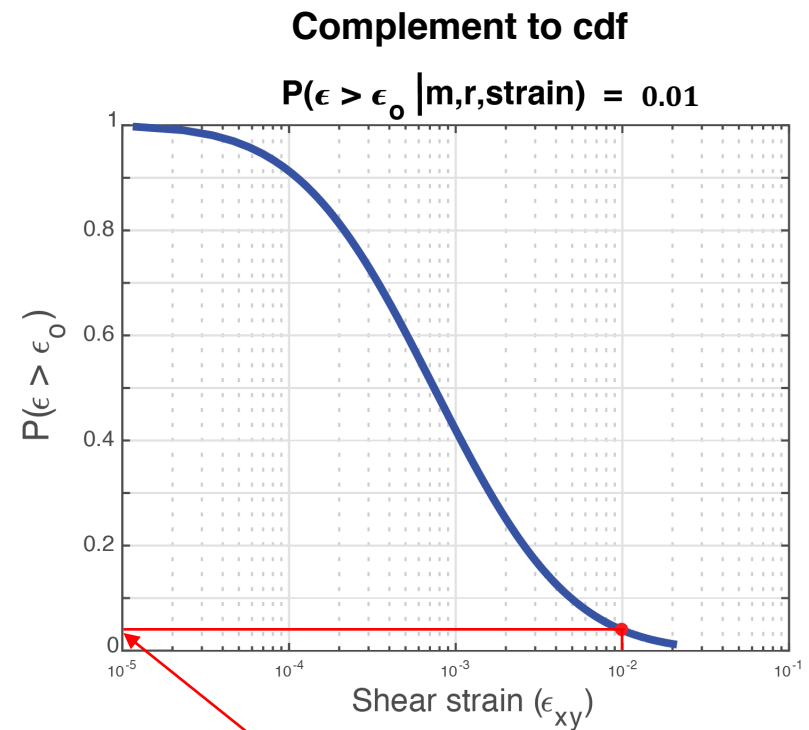
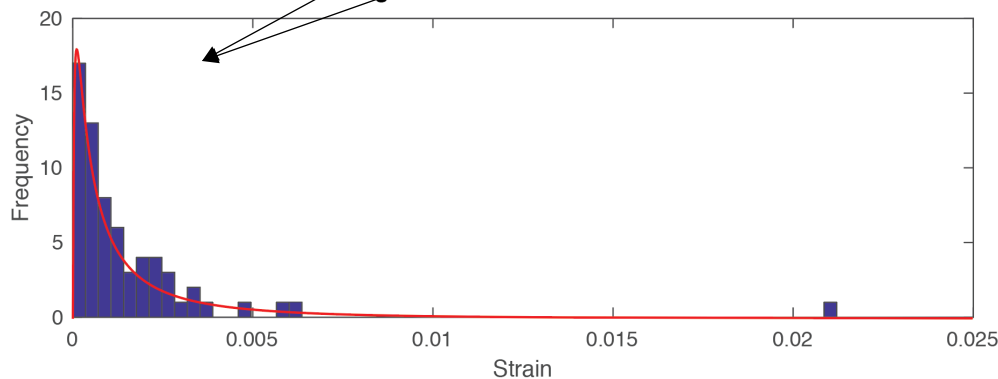


Estimate second term (prob. of exceedance)

- At each distance we get a distribution → **fit lognormal** → **survivor fn.** → exceedance term.



Histogram of strain at distance:168 m



$$\lambda(\epsilon \geq \epsilon_0)_{xyz} = \alpha P[sr \neq 0 | m] P[\epsilon > \epsilon_{inelastic} | r, z] P[\epsilon \geq \epsilon_0 | r, m, \epsilon_{inelastic}]$$

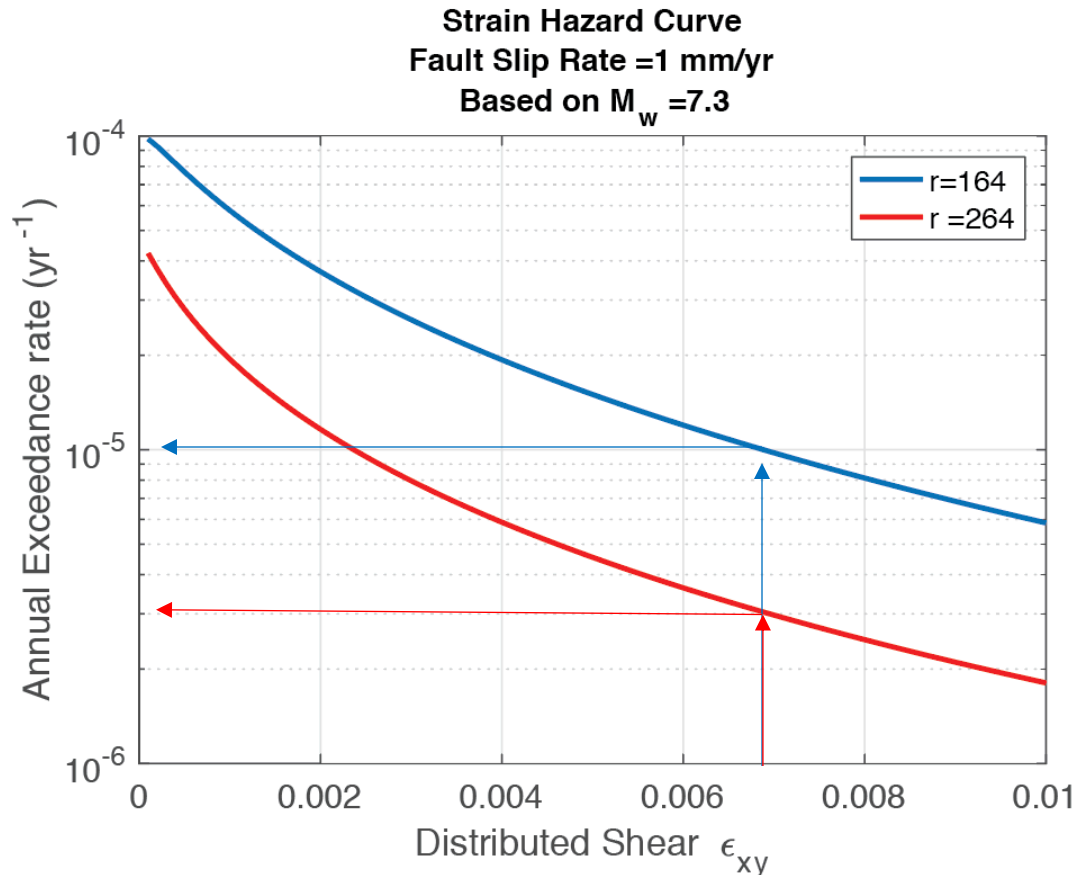
Wells & Coppersmith (1994)

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Product: Hazard curve

Annual exceedance of 0.007 strain occurring 164 m away from main fault is 10^{-5}

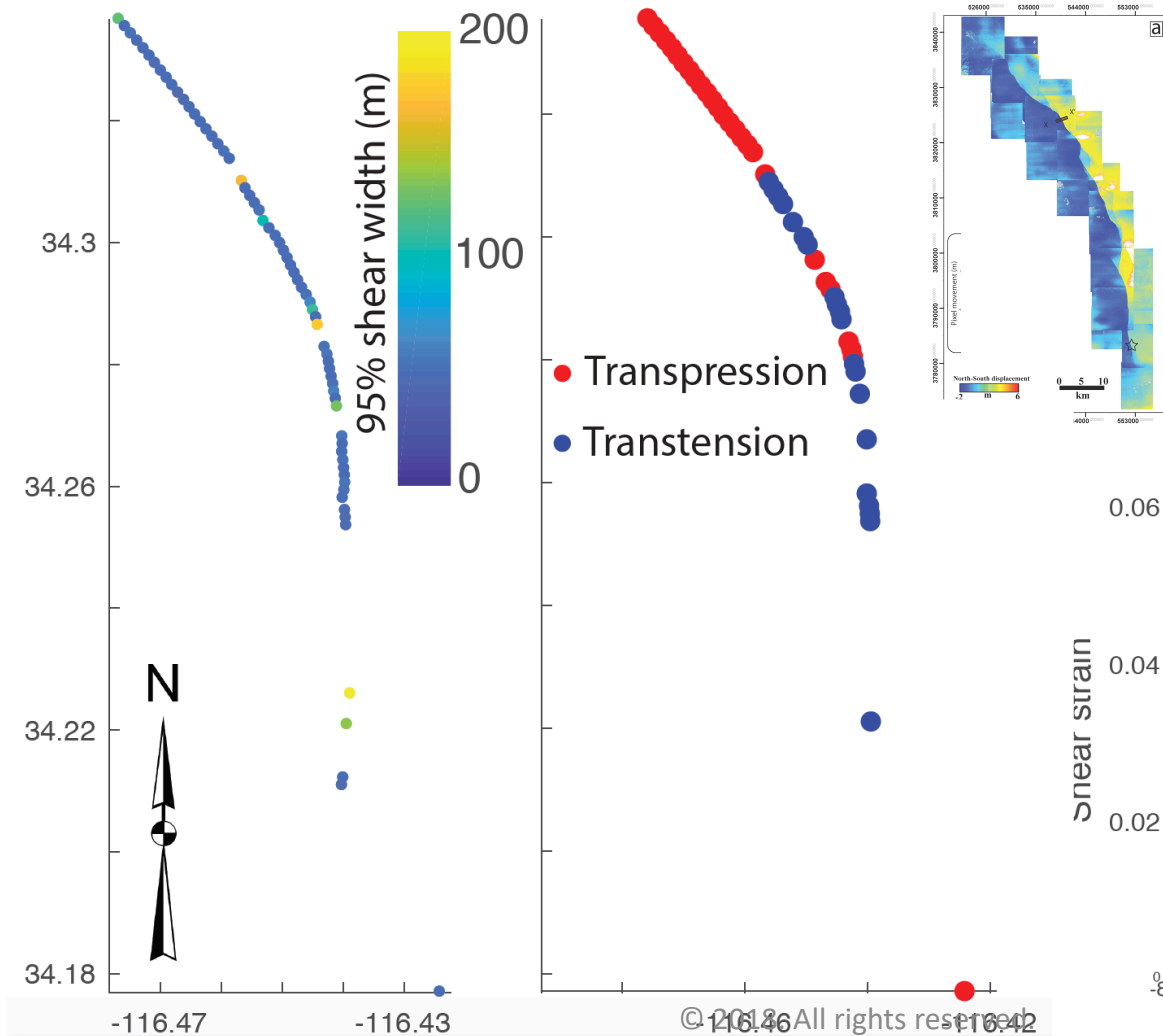
- i.e., there is a 10^{-5} prob. of this event occurring in a given year.
- 1 in a 100,000 yr 'event'



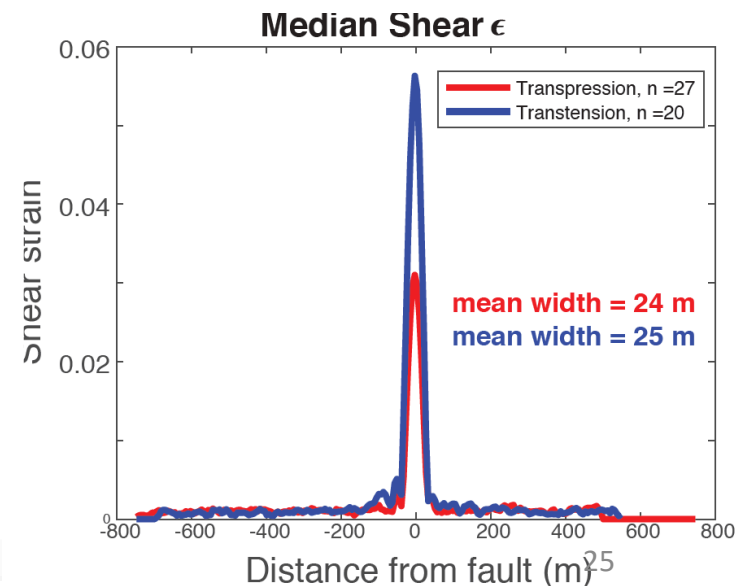
Annual exceedance of 0.007 strain occurring 264 m away from main fault is 3×10^{-6}

- Product: annual exceedance of shear strain at some distance, not distributed displacement.
- But can integrate over a distance/area of interest
→ total expected displacement.

Reducing epistemic uncertainty: Assess effect of... fault zone compression or extension



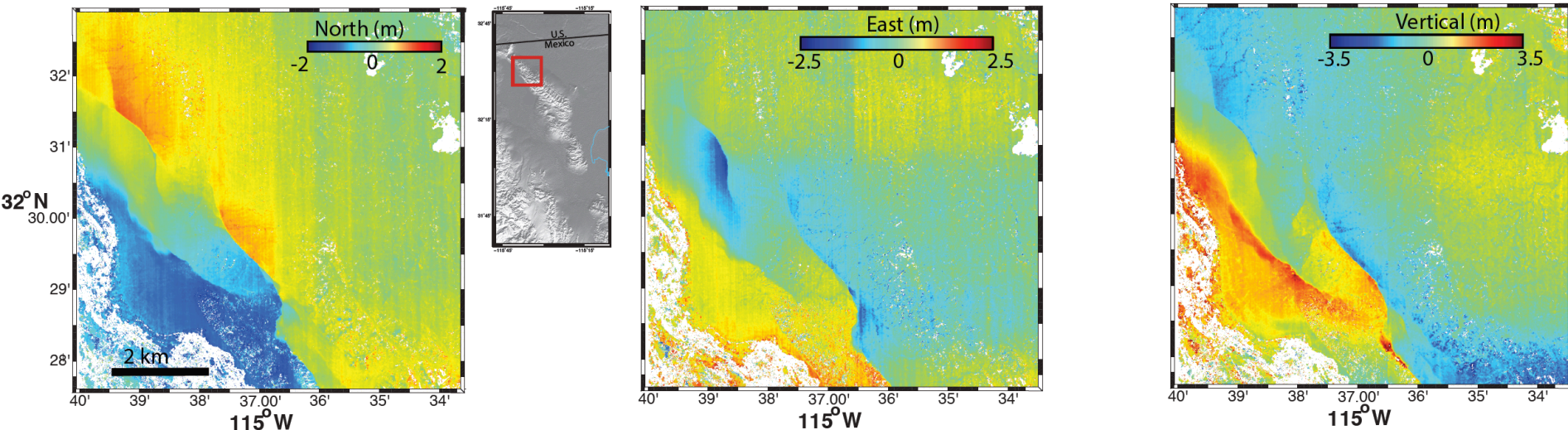
- Is fault zone width narrower when under compression, and more distributed under extension?



PFDHA for thrust + normal events

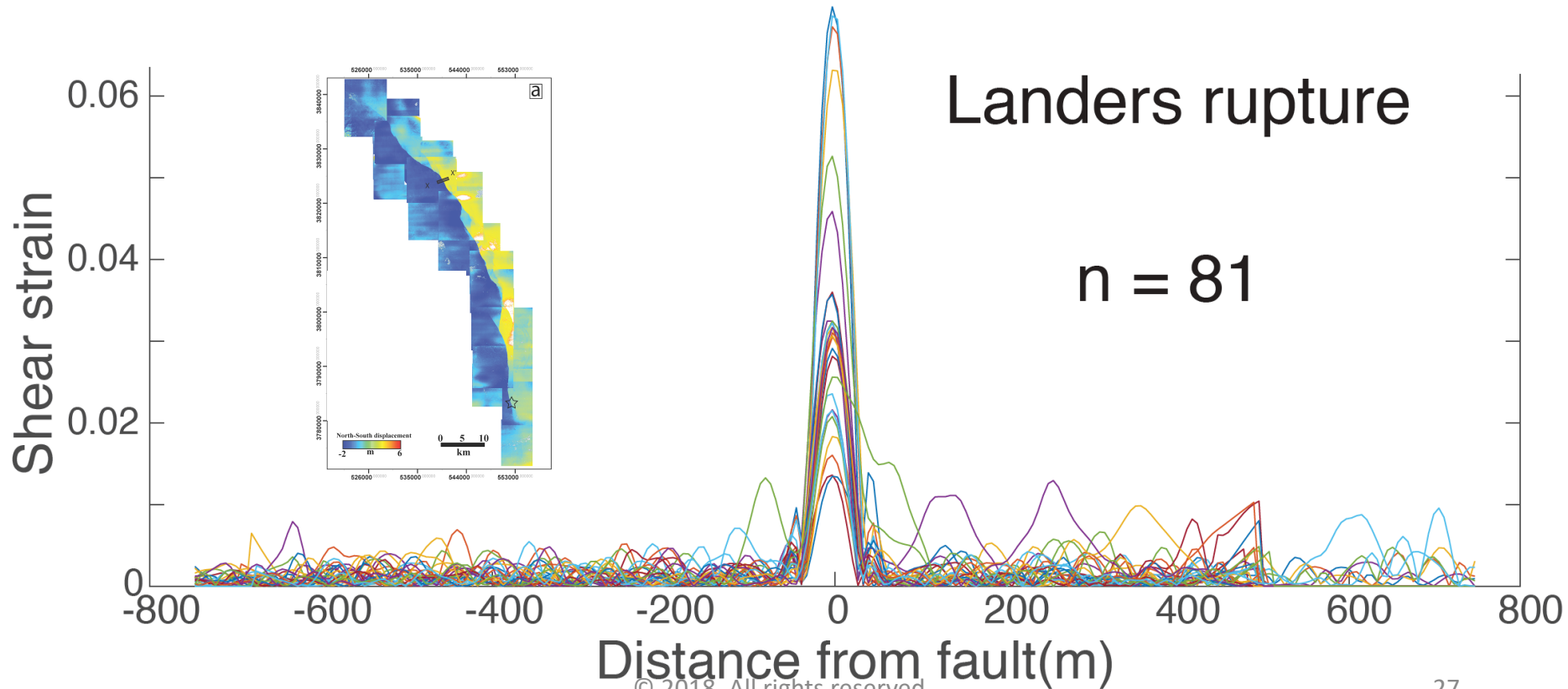
- Normal + thrust typically asymmetric HW, FW
- 3D image correlation method is now possible

2010 Mw 7.2 El-Mayor Cucapah

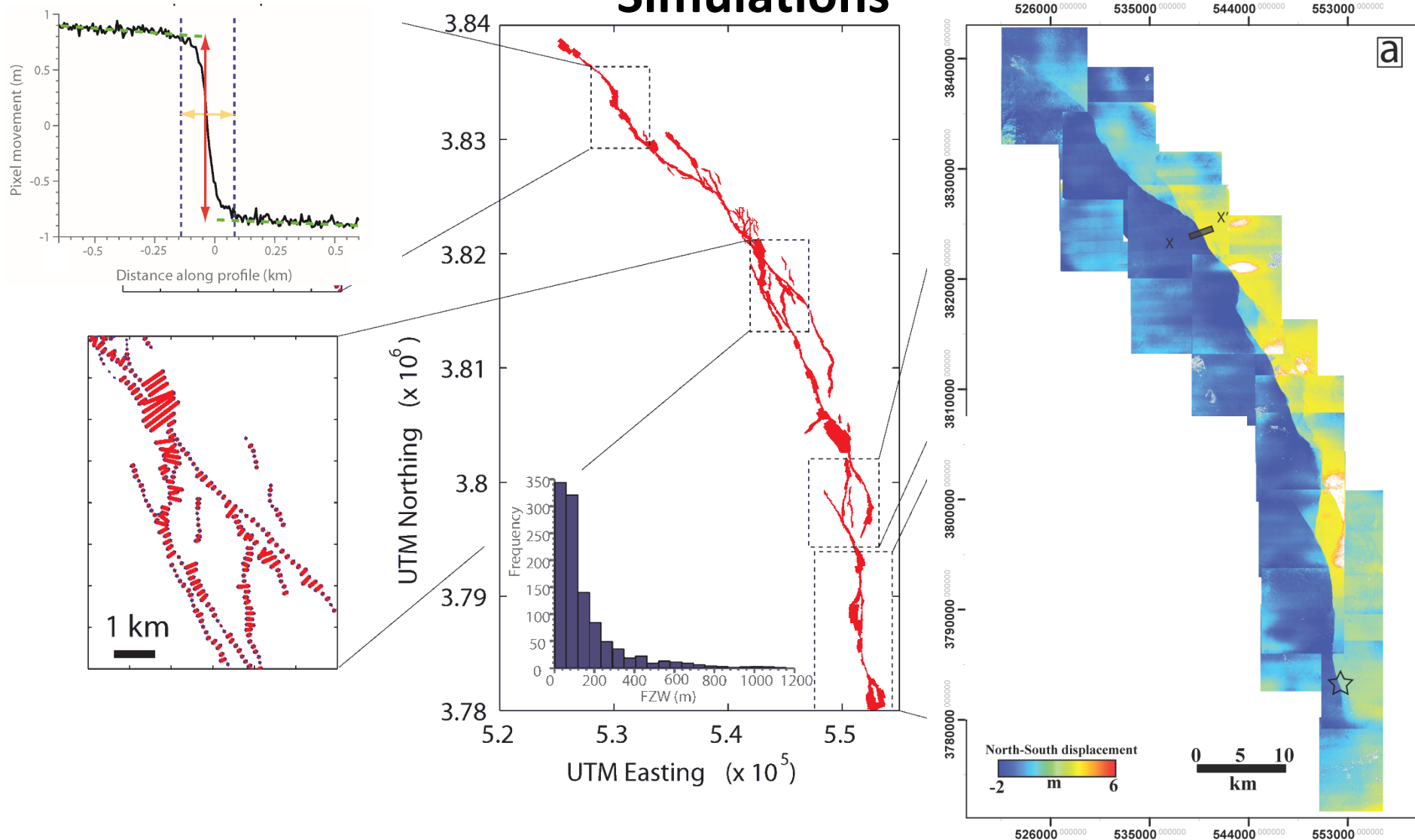


Moving away from ergodic PFDHA

- **Ergodic system** = treat variability in displacement (strain) data measured from different faults (spatial uncertainty) as an variability over time at a single point (temporal variation).



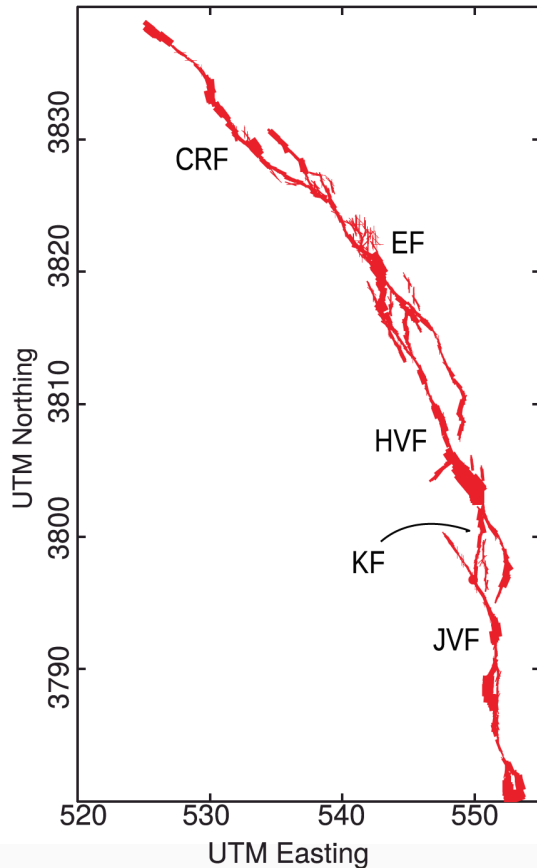
Next-next Gen PFDHA: Using Numerical Simulations



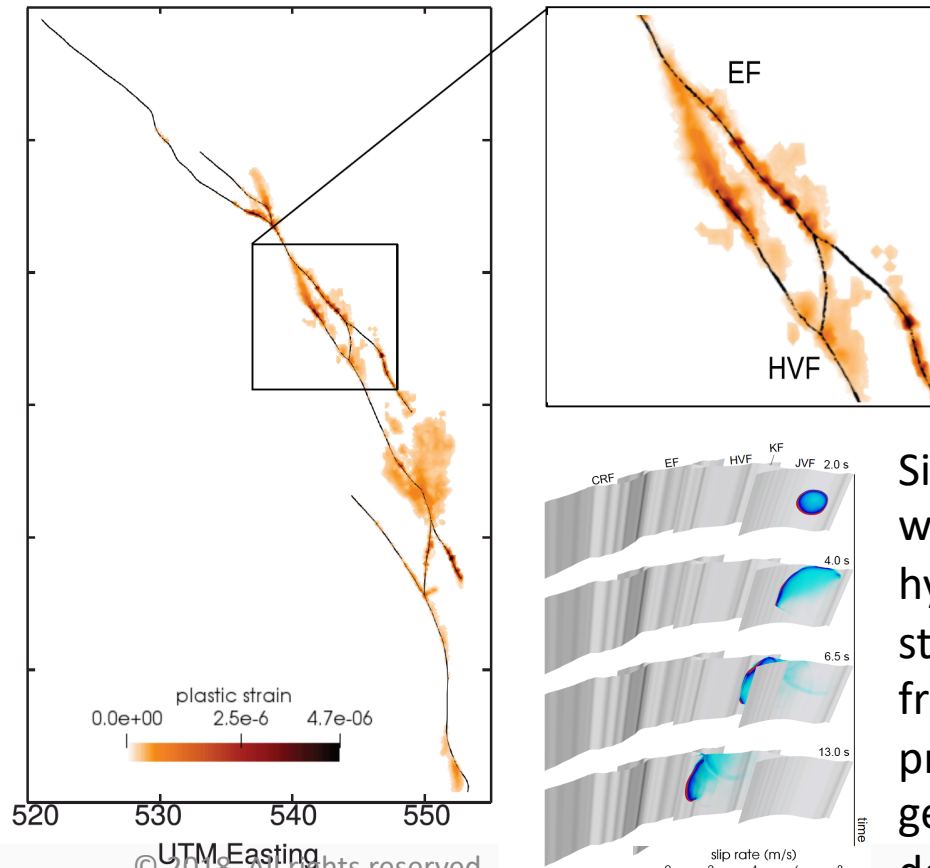
PFHDA Using Numerical Simulations

- Instead of using variations of faulting from different earthquakes along strike → to define empirical faulting probabilities → use numerical simulations

Milliner et al. (2016)



Wollherr et al. (2019)



Simulate ruptures with various hypocenters, stress states, frictional properties, geometries at depth...

Conclusions & Future Work

- Geodetic data holds promise for PFDHA:
 - Now have adequate image resolution ($\leq 1\text{m}$ resolution)
 - Many data points ($n > 1000$)
 - Lower uncertainty ($\sigma = 10\text{ cm}$)
 - Moderate number of earthquakes ($n = 10$)
- **More reliable probability models of distributed faulting**
- Future work:
 - Develop standard geodetic method
 - Assess effects of near-surface geology + fault zone compression/extension
 - Explore PFDHA for thrust and normal faults